The MARATHON Experiment With a 24 GeV JLab Beam*

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Deep Inelastic Scattering and Quark Parton Model

- Cross Section-Nucleon/Nuclear structure functions F_1 and F_2

(E : incident electron energy, E' : scattered electron energy, θ : scattering angle)

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4\left(\frac{\theta}{2}\right)}\left[\frac{F_2(\nu, Q^2)}{\nu}\cos^2\left(\frac{\theta}{2}\right) + \frac{2F_1(\nu, Q^2)}{M}\sin^2\left(\frac{\theta}{2}\right)\right]$$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1 \nu}\left(1 + \frac{\nu^2}{Q^2}\right) - 1 \qquad \nu = E - E' \qquad Q^2 = 4EE'\sin^2(\theta/2)$$

- In deep inelastic scattering (DIS) the target nucleus breaks up.
- Quark-Parton Model (QPM) interpretation in terms of quark probability distributions $q_i(x)$ [x: Bjorken variable]:

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x) \qquad F_2(x) = x\sum_i e_i^2 q_i(x) \qquad x = Q^2/2M\nu$$

- Since R is the same for all nuclei, the cross section ratio of two nuclei is equal to the ratio of their F_2 structure functions.

F_2^n/F_2^p in the Quark Parton Model

- Assume isospin symmetry:

$$u^p(x) \equiv d^n(x) \equiv u(x) \qquad \bar{u}^p(x) \equiv \bar{d}^n(x) \equiv \bar{u}(x)$$

$$d^p(x) \equiv u^n(x) \equiv d(x) \qquad \bar{d}^p(x) \equiv \bar{u}^n(x) \equiv \bar{d}(x)$$

$$s^p(x) \equiv s^n(x) \equiv s(x) \qquad \bar{s}^p(x) \equiv \bar{s}^n(x) \equiv \bar{s}(x)$$

- Proton and neutron structure functions:

$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$

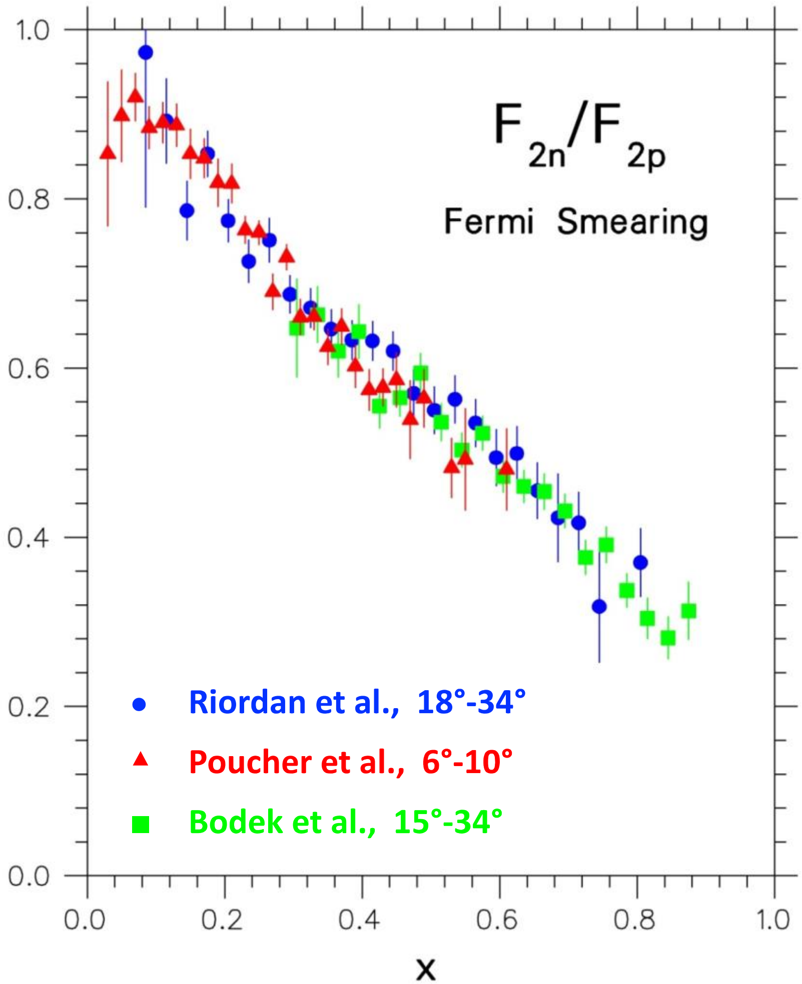
$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

- Nachtmann inequality: $1/4 \leq F_2^n / F_2^p \leq 4$

SLAC Measurements

End Station A, 1968-1972

Friedman, Kendal, Taylor, Nobel 1990



F_2^n/F_2^p extracted from proton and deuterium deep inelastic data using the Hamada-Johnston nucleon-nucleon potential in a Fermi-smearing model.

Data in disagreement with *SU(6)* prediction of 2/3=0.67!

Data in agreement with the diquark model of Feynman and others.

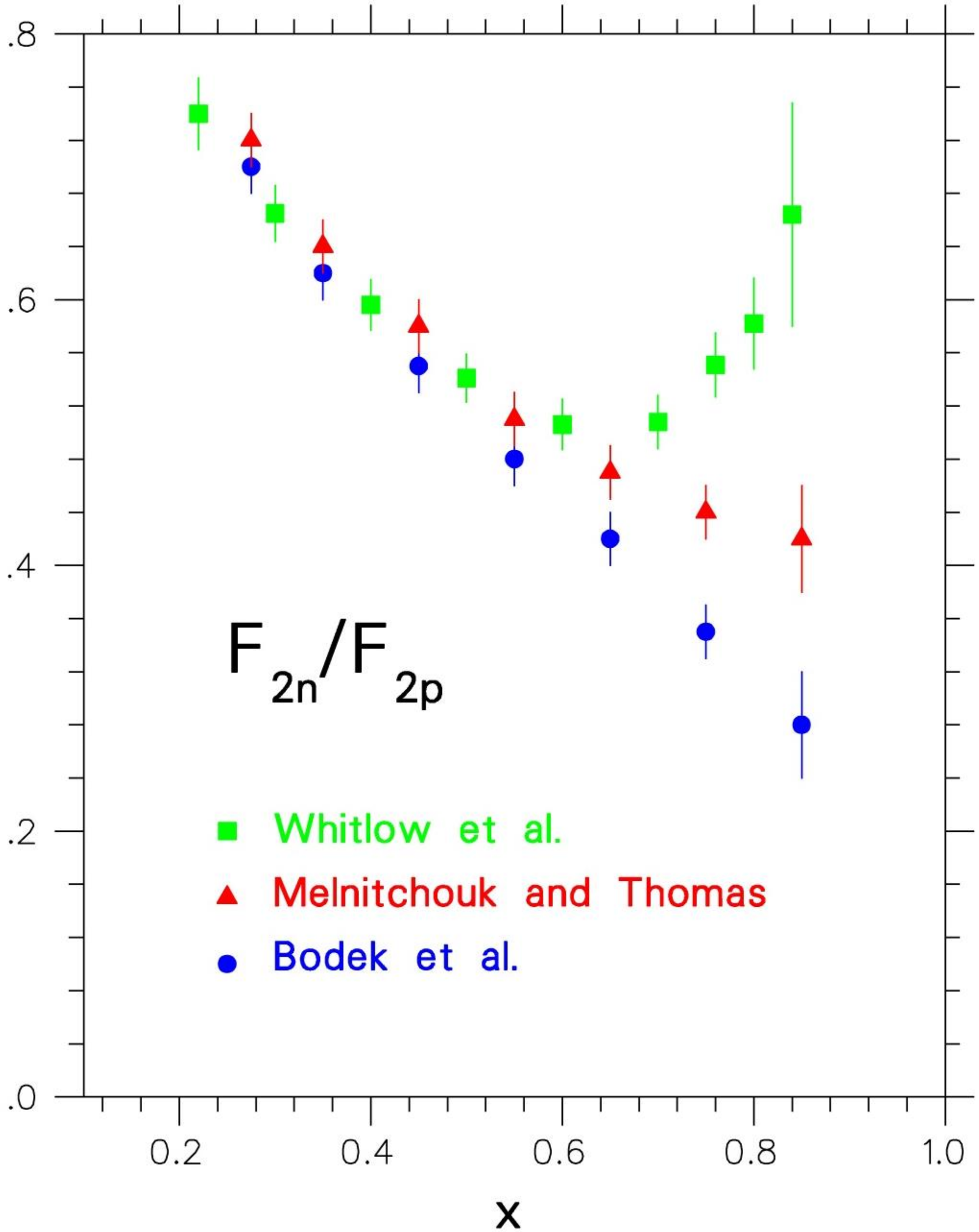
F_2^n/F_2^p is bounded, between 1/4 and 4, as predicted (Nachtmann inequality).

At low *x*, see quarks dominate with the *u*, *d*, and *s* quark distributions being equal.

High momentum quarks in the proton (neutron) are up (down) quarks.

The *d/u* quark ratio is extracted from F_2^n/F_2^p , after subtraction of the *s* quark contribution.

Nucleon F_2 Ratio Extraction Revisited



SLAC DIS Data

Whitlow (1992): Assumes EMC effect in deuteron (Frankfurt and Strikman data-based Density Model)

Melnitchouk &Thomas (1996): Relativistic convolution model with empirical binding effects

Bodek (1992): Non-relativistic Fermi smearing model with Paris N-N potential. Note: at large *x* there is significant dependence on the N-N potential used (Paris, Bonn, Argonne, etc.)

F_2^n/ F_2^n, d/u Ratios and A_1 Limits for $x\rightarrow 1$

	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Diquark Model/Feynman	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
Quark Counting Rules	3/7	1/5	1	1

A_1: Asymmetry measured with polarized electrons and nucleons. Equal in QPM to probability that the quark spins are aligned with the nucleon spin.

A_1^p, A_1^n: Extensive experimental programs at CERN, SLAC, DESY and JLab (6 GeV and 12 GeV Programs)

Nucleon F_2 Ratio Extraction from ^{3}He/^{3}H

- Form the "Super-Ratio" of EMC-type ratios for A=3 mirror nuclei:

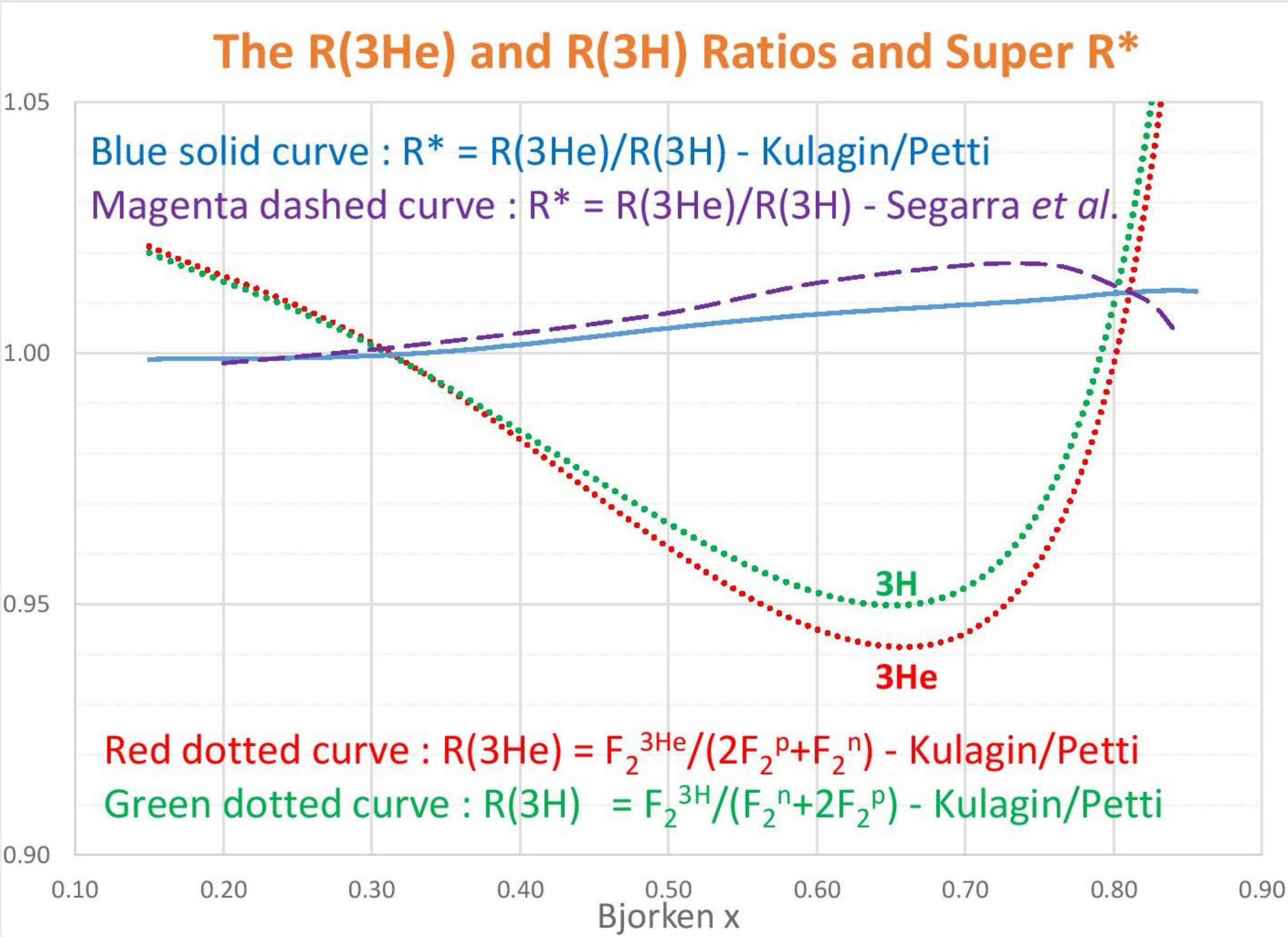
$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \qquad R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n} \qquad R^* = \frac{R(^3He)}{R(^3H)}$$

- Solve above equations for the $A=3$ F_2 structure function ratio:

$$\frac{\sigma^{^3He}}{\sigma^{^3H}} = \frac{F_2^{^3He}}{F_2^{^3H}} = R^* \frac{2F_2^p + F_2^n}{F_2^p + 2F_2^n}$$

- Solve for the nucleon F_2^n/F_2^p ratio and calculate it, using R^* from a reliable theoretical/phenomenological model (value of R^* is very close to unity with small uncertainty), and the measured $A=3$ DIS cross section ratio:

$$\frac{F_2^n}{F_2^p} = \frac{2R^* - \sigma^{^3He}/\sigma^{^3H}}{2\sigma^{^3He}/\sigma^{^3H} - R^*}$$

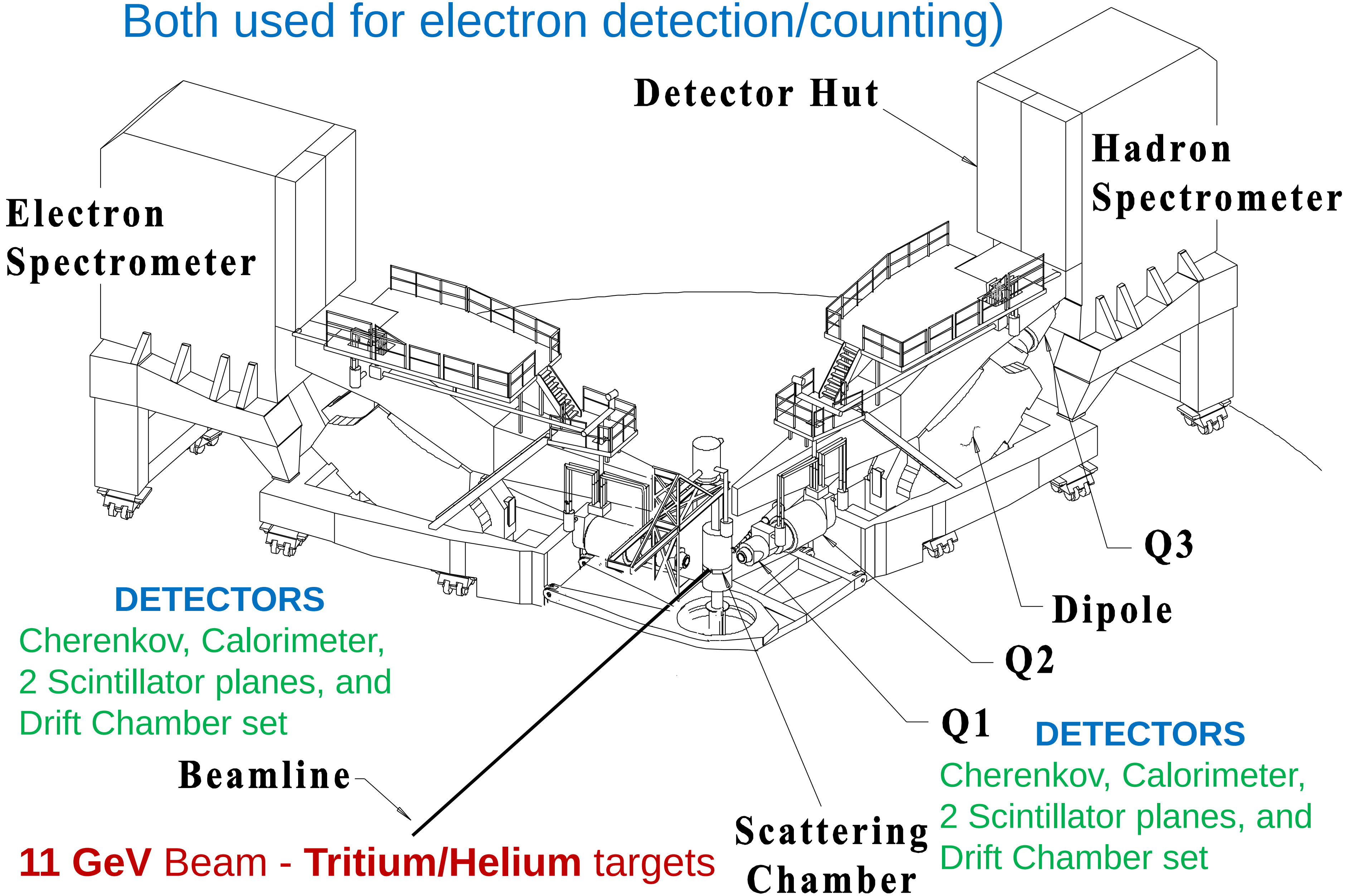

The R(3He) and R(3H) Ratios and Super R*
Blue solid curve : R* = R(3He)/R(3H) - Kulagin/Petti
Magenta dashed curve : R* = R(3He)/R(3H) - Segarra et al.
3H
3He
Red dotted curve : R(3He) = $F_2^{3He}/(2F_2^p+F_2^n)$ - Kulagin/Petti
Green dotted curve : R(3H) = $F_2^{3H}/(F_2^n+2F_2^p)$ - Kulagin/Petti
1.05
1.00
0.95
0.90
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
Bjorken x

The JLab MARATHON Experiment

- MARATHON was designed to extract the F_2^n/F_2^p ratio by measuring at medium/high x the ratio of ^{3}H and ^{3}He DIS cross sections, in which many theoretical uncertainties cancel out.
- It used the 2 High Resolution Spectrometers (HRS) of Hall A and a cryogenic gas target system of ^{3}H, ^{3}He, ^{2}H, and ^{1}H.
- Scattered electrons in each HRS were identified using a gas threshold Cherenkov detector and a lead-glass calorimeter. Their tracks were measured with a drift chamber set;
- It covered, using a 10.6 GeV electron beam, the Bjorken x range $0.19 < x < 0.83$ with $3 < Q^2 < 12$ (GeV/c)^2 and $1.8 < W < 3.5$ GeV/c^2.
- Other than the (unusual, used only in extraordinary cases) ^{3}H target, MARATHON is a typical DIS experiment.

JLab Hall A HRS Systems - MARATHON

Both used for electron detection/counting)



DETECTORS

Cherenkov, Calorimeter,
2 Scintillator planes, and
Drift Chamber set

DETECTORS

Cherenkov, Calorimeter,
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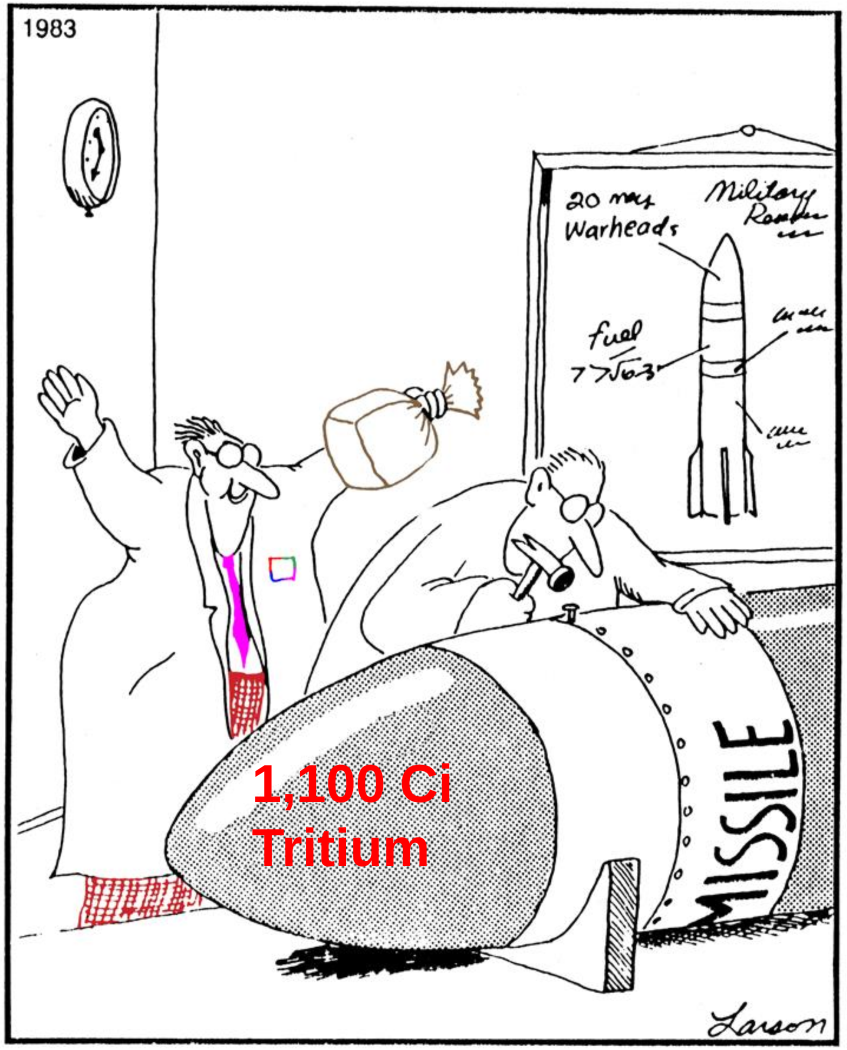
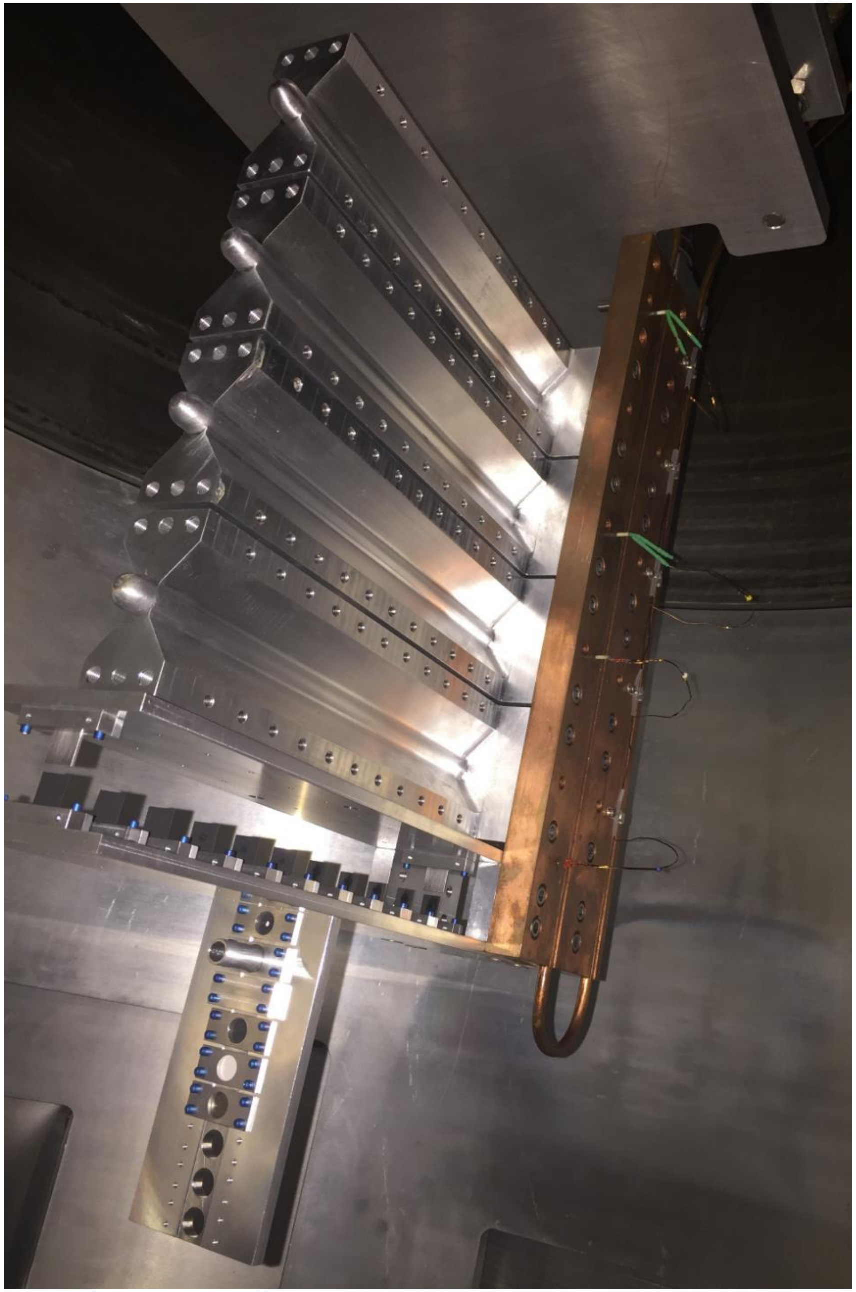
Drift Chamber set

11 GeV Beam - **Tritium/Helium** targets

The ^3H, ^2H, ^1H, ^3He High Pressure Gas Cells Target Ladder Structure

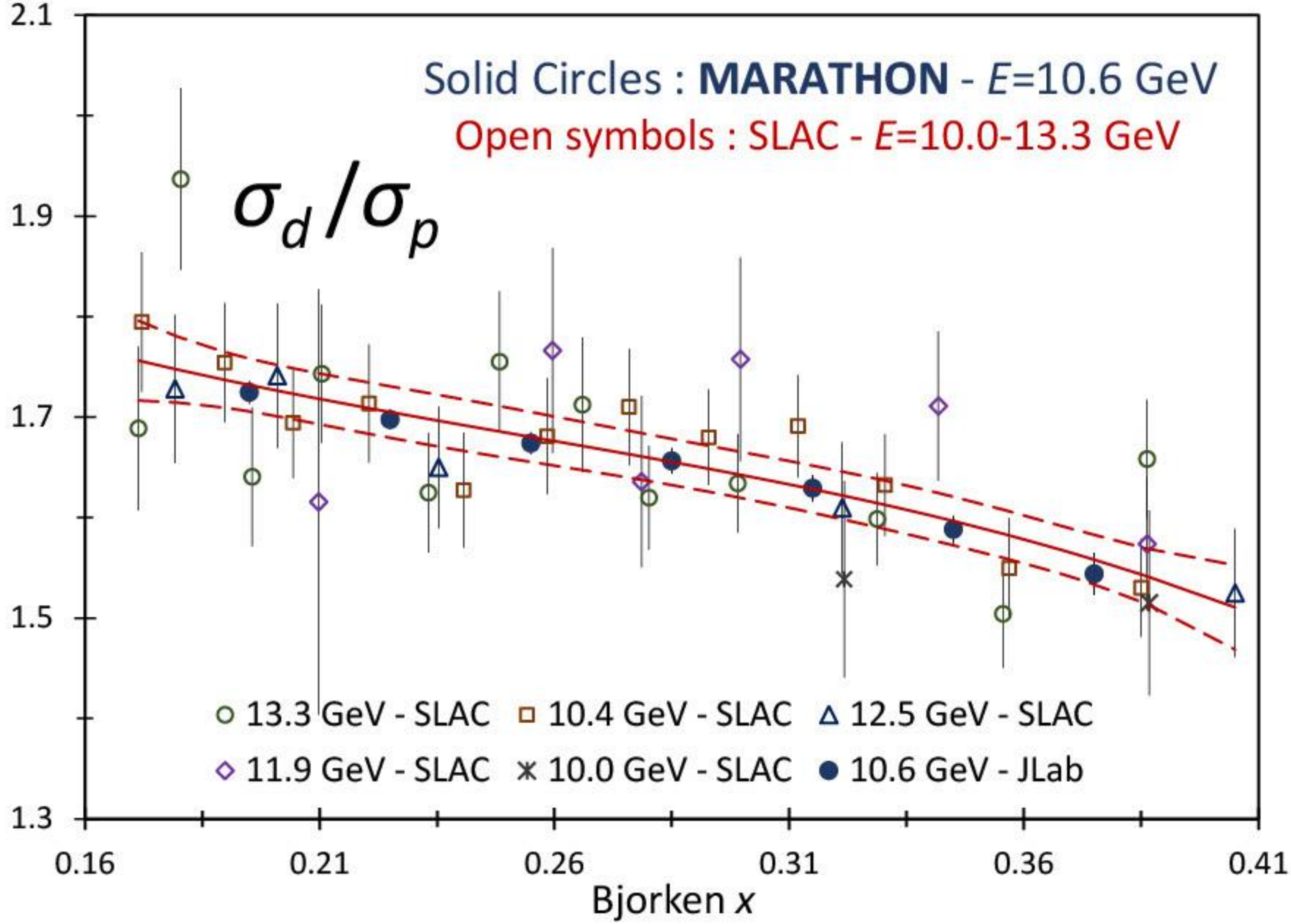


Tritium cell was filled at the Tritium Handling Facility of Savannah River National Laboratory (1,100 Curies).



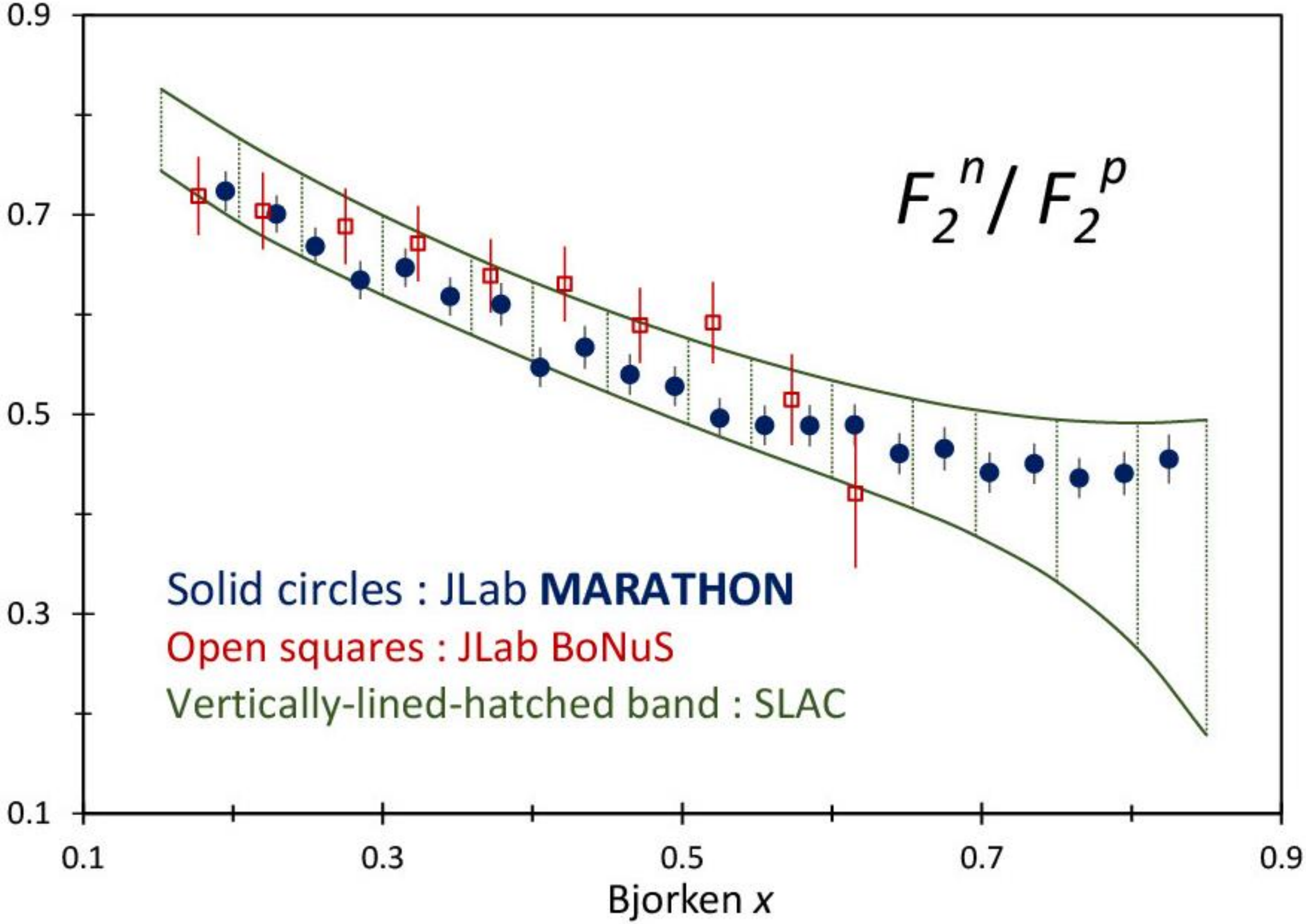
MARATHON *d/p* DIS Calibration Data

- MARATHON measured the ratio of *d/p* DIS yield at low *x* values (around $x=0.3$) with *high precision*. The *accuracy* of the *d/p* results is dominated by the gas target uncertainties (~0.5%).
- The *d/p* ratio data, are in excellent agreement with the SLAC *benchmark/reference* data, taken at similar kinematics, by the SLAC/MIT group, with the 8 GeV/*c* Spectrometer.
- The F_2^n/F_2^p calibration values have been determined from the ^{2}H and ^{1}H data using $F_2^n/F_2^p = [(F_2^d/F_2^p)/R^*]-1$, where R^* is the deuteron EMC-type ratio $R^* = F_2^d/(F_2^n + F_2^p)$, calculated from a model by Kulagin and Petti, which is, at low/medium *x*, in very good agreement with data from JLab BoNuS and SLAC E139 expts., and a recent nuclear DIS model and by Segarra *et al*.
- The *d/p*-extracted F_2^n/F_2^p values in the vicinity of $x=0.3$ have been used to normalize F_2^n/F_2^p from the ^{3}H/^{3}He ratio data.

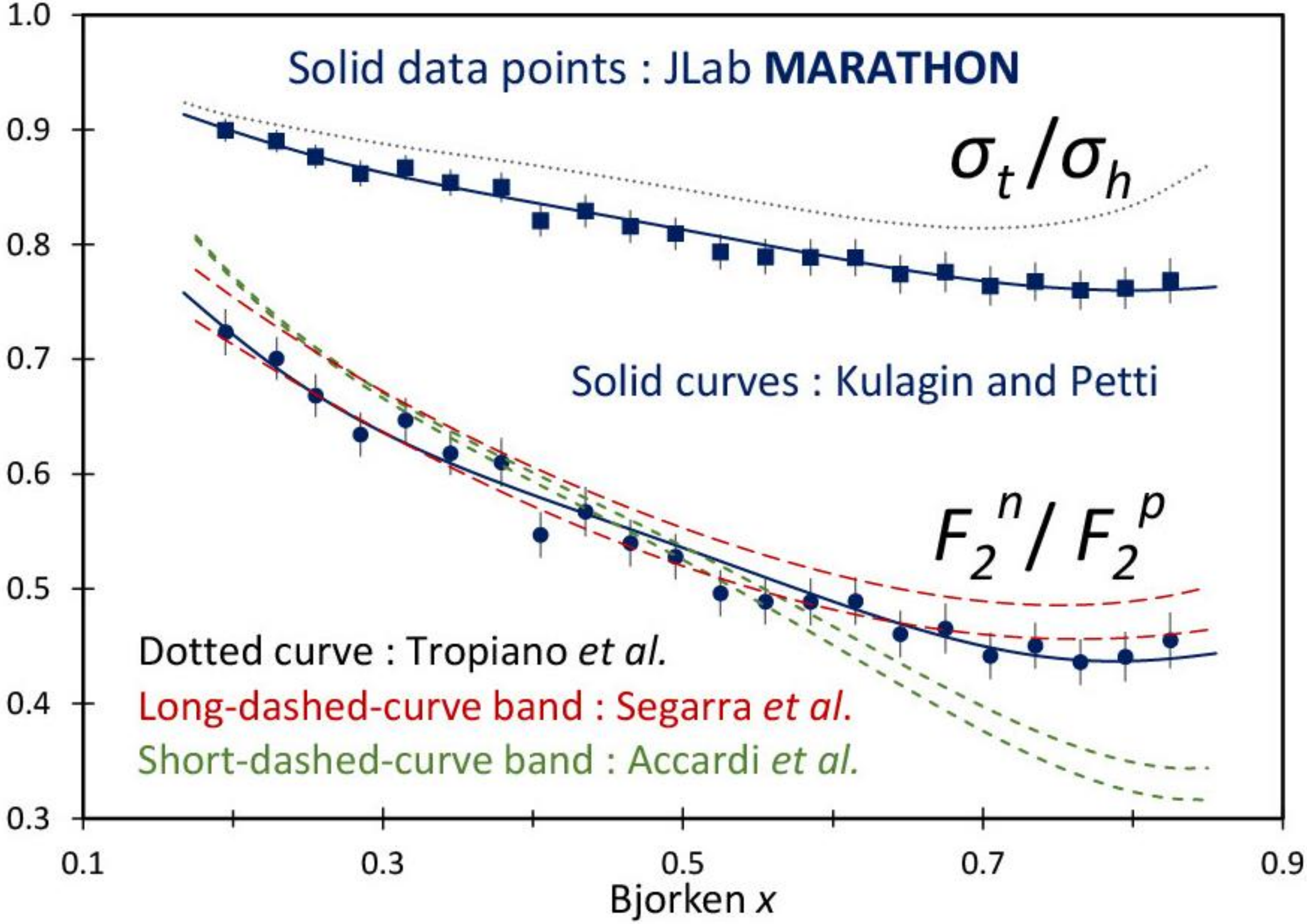

Solid Circles : MARATHON - E=10.6 GeV
Open symbols : SLAC - E=10.0-13.3 GeV
σd/σp
13.3 GeV - SLAC
10.4 GeV - SLAC
12.5 GeV - SLAC
11.9 GeV - SLAC
10.0 GeV - SLAC
10.6 GeV - JLab
2.1
1.9
1.7
1.5
1.3
0.16
0.21
0.26
0.31
0.36
0.41
Bjorken x

MARATHON $^3H/^3He$ DIS Data

- F_2^n/F_2^p has been determined from ^{3}H (*t*, *triton*) and ^{3}He (*h*, *helion*) DIS as $F_2^n/F_2^p=[2R^*-(F_2^h/F_2^t)]/[2(F_2^h/F_2^t)-R^*]$, where R^* is the ratio of the EMC-type ratios $F_2^t/(F_2^n+2F_2^p)$ and $F_2^h/(2F_2^p+F_2^n)$, as calculated from a theory model by S. Kulagin and R. Petti, developed prior to the experiment.
- The F_2^h/F_2^t K-P convolution model, which uses the $A=3$ spectral functions by the Rome group, is in excellent agreement with the MARATHON *h*/*d*, *t/d*, and *h/t* ratio DIS data.
- F_2^n/F_2^p as calculated from the measured ^{3}H/^{3}He ratio was compared to F_2^n/F_2^p as calculated from the measured *d/p* ratio. In order to match the values for the two measurements in the vicinity of $x=0.3$, it was found that the ^{3}He/^{3}H cross section ratio must be scaled up (normalized) by 2.5%.



Accepted for publication by Physical Review Letters



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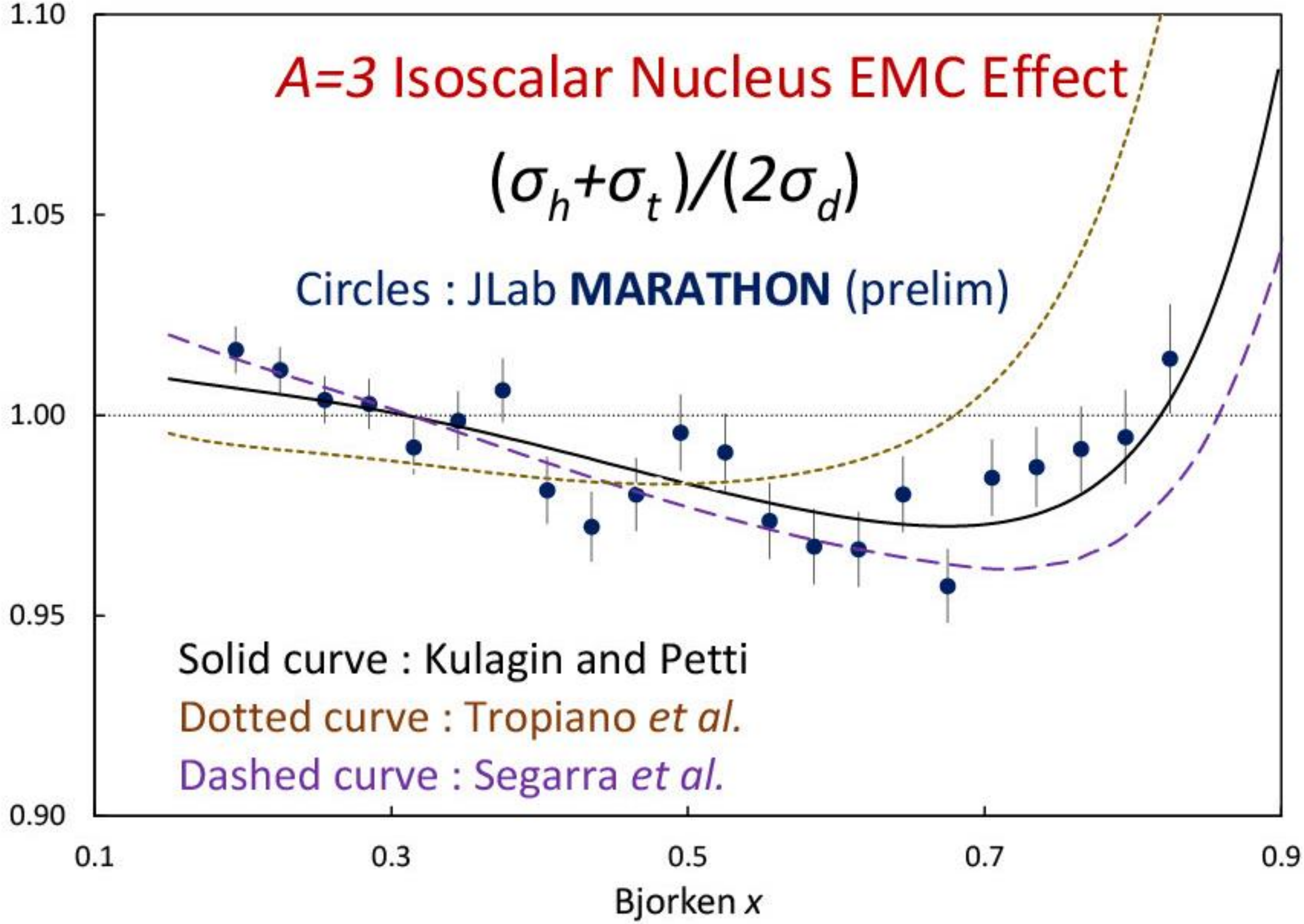


Paper in preparation for submission for publication

MARATHON @ 24 GeV JLab (I)

- A 24 GeV electron beam will be ideal for extending the MARATHON measurements to larger values of Bjorken x, up to x = 0.9, and for essentially doubling the existing four momentum range, up to $Q^2 = 22$ (GeV/c)^2.
- A 24 GeV beam will also allow for more precise and extended measurements of the nucleon spin structure functions.
- A new experiment would have to be performed in Hall C using mainly the Super High Momentum Spectrometer.
- It is assumed that a closed, low activity Tritium target similar to the one used in MARATHON can be safely employed.
- To extend the present measurements to the largest x possible while being in the DIS regime [$W^2 > 3.5$ [(GeV/c^2)^2], it is desirable that the density of the MARATHON gas targets are doubled or tripled (including the tritium target).

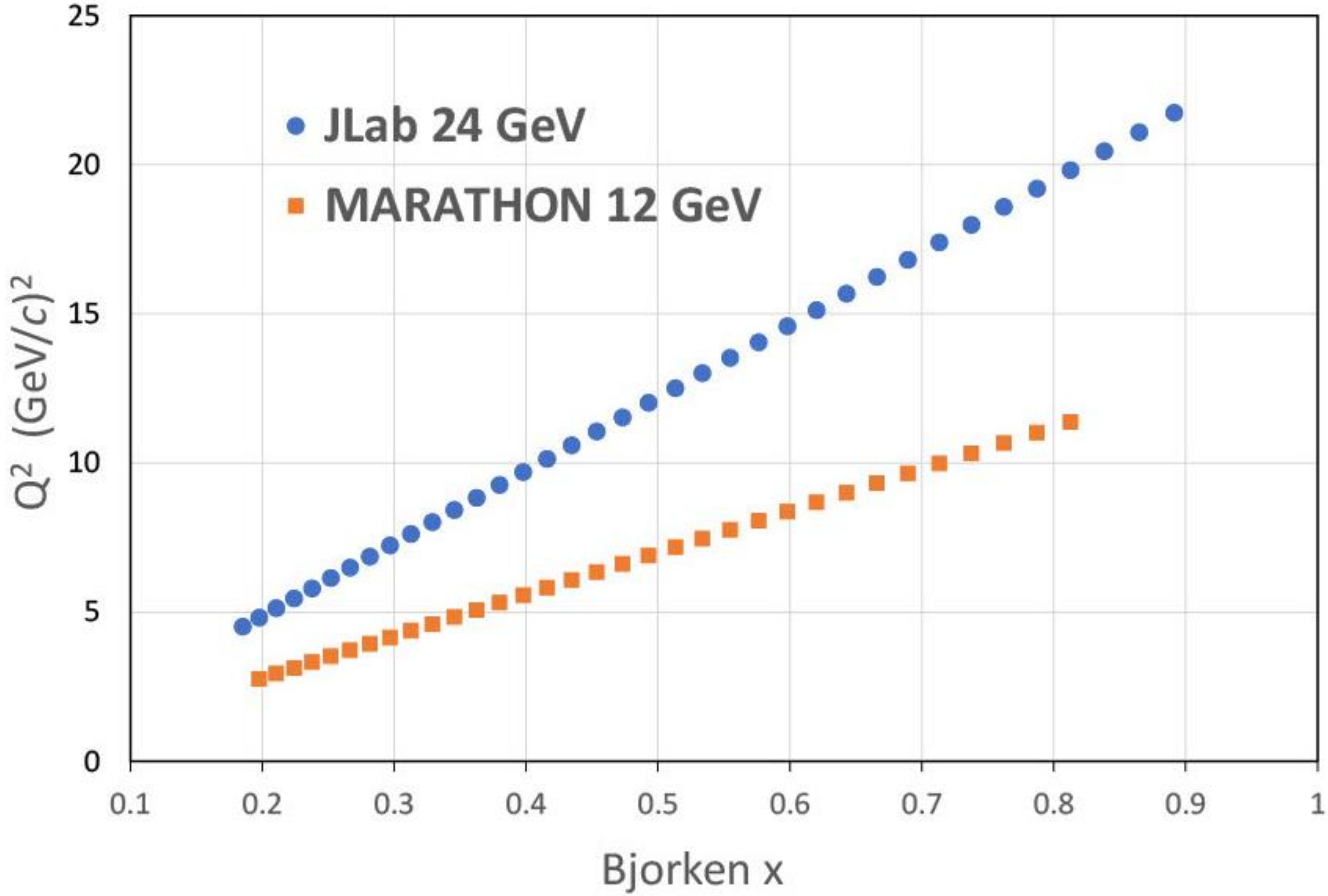
MARATHON @ JLab 24 GeV(II)

Hall C HMS and SHMS Systems

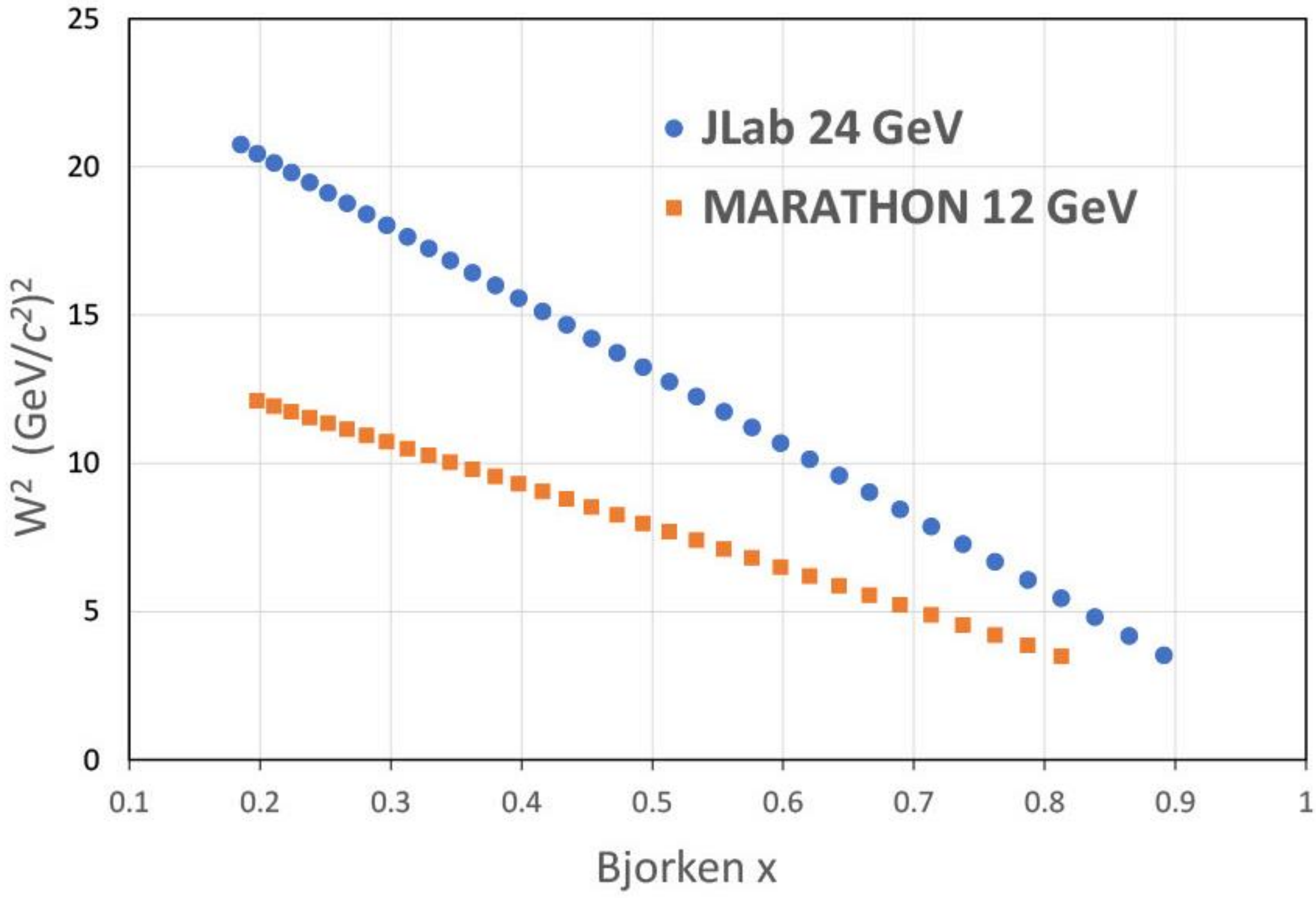
MARATHON @ 24 GeV JLab (III)

- Overall, the new experiment will be similar to MARATHON and will use the existing Hall C spectrometer apparatuses.
- Both HMS and SHMS will be used up to their maximum central momenta (7.3 and 11 GeV/*c*).
- HMS (SHMS) to cover the angular range 10^o-25^o (7.5^o-16.5^o).
- To minimize systematic errors the target cells will be cycled frequently in the beam, as in MARATHON.
- For safety reasons, the current will be limited to ~25 micro-amps, as in MARATHON.
- To eliminate electrons originating from the target cell end caps an alternate optics tune of the SHMS may be necessary.
- The experiment will measure, as in MARATHON, both the nucleon F_2^n/F_2^p ratio and the EMC effect for the A=3 nuclei.

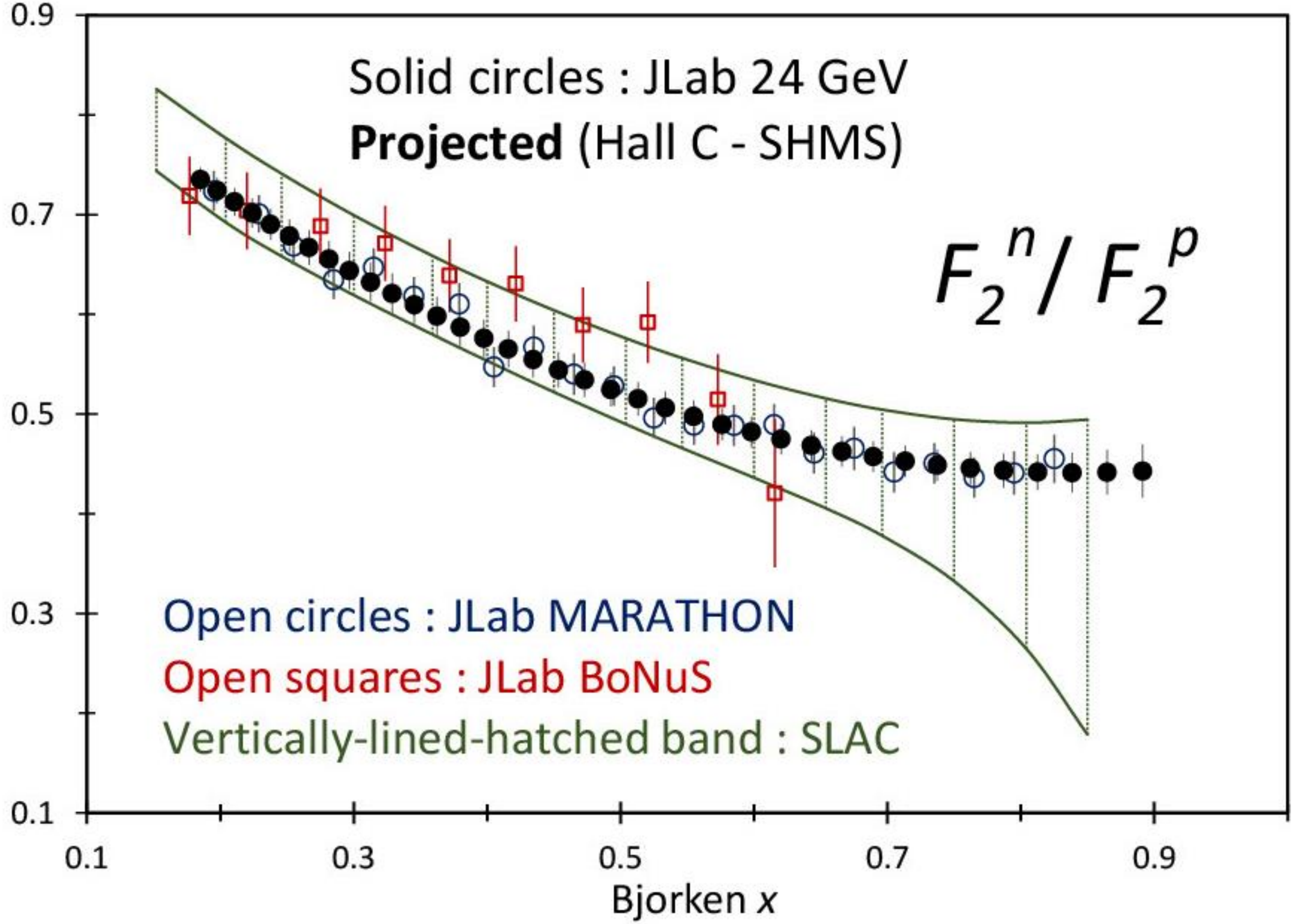
MARATHON @ 24 GeV JLab (IV)



MARATHON @ 24 GeV JLab (V)

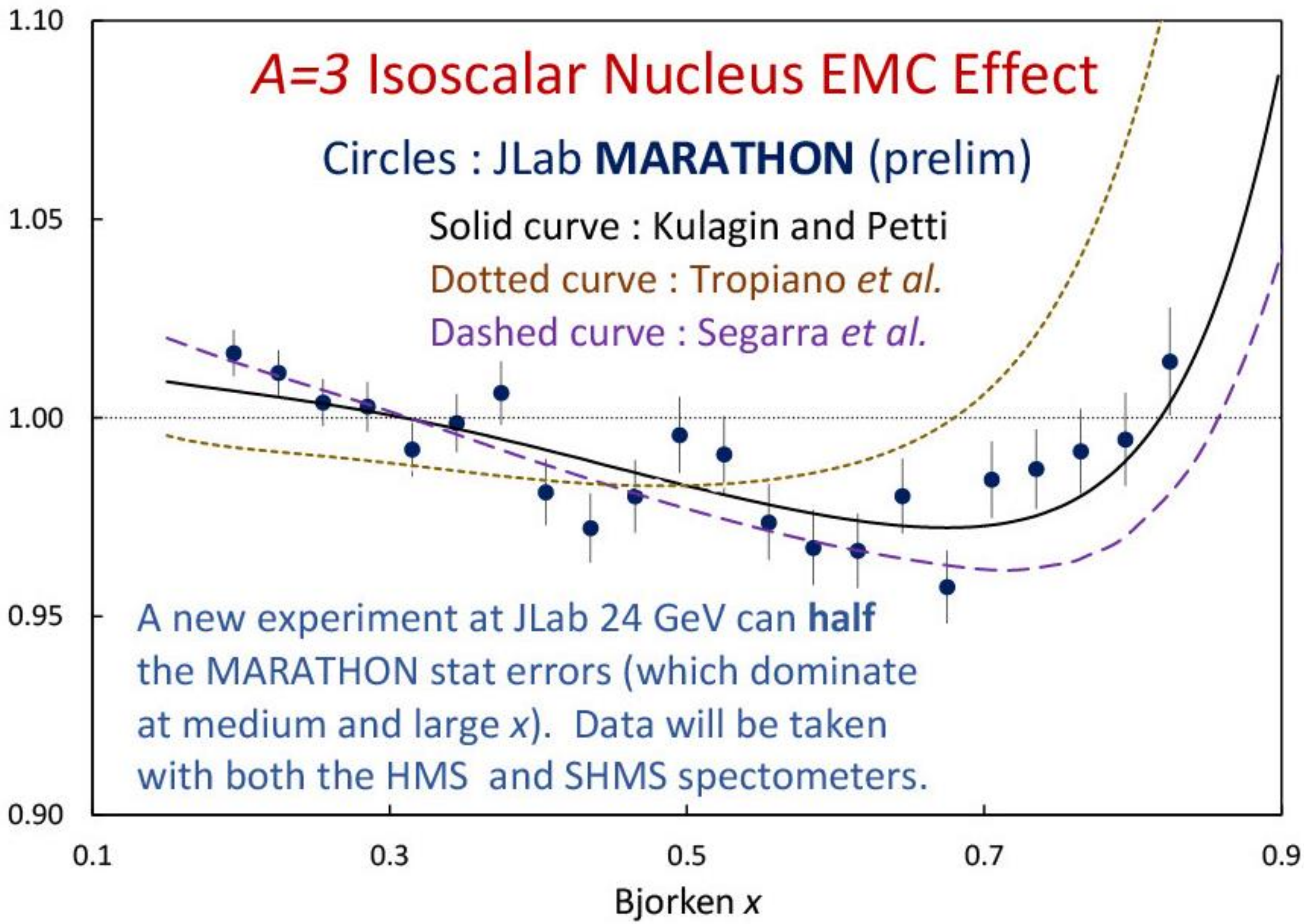


MARATHON @ 24 GeV JLab (VI)



~ 2 months of running time

MARATHON @ 24 GeV JLab (VII)



Summary

- MARATHON has provided high quality F_2^n/F_2^p data at medium and large values of Bjorken x that are free of inherent uncertainties present in the SLAC data extracted from d/p DIS.
- MARATHON has also provided a high quality measurement of the isoscalar EMC effect of the $A=3$ nucleus (a nucleus made up of 1.5 proton and 1.5 neutron).
- JLab with a 24 GeV electron beam can significantly extend the kinematic range of the 12 GeV MARATHON experiment.
- SHMS in JLab Hall C can be used to extend F_2^n/F_2^p up to x = 0.9, doubling the MARATHON four momentum range up to Q^2 = 22 (GeV/c)^2, with W^2 > 3.5 [(GeV/c^2)^2.
- HMS and SHMS data can be used to improve the existing MARATHON measurements of the EMC effect of the $A=3$ mirror nuclei.